

A Comprehensive Review of Proppant Selection in Unconventional Reservoirs

Mian Umer Shafiq, Shabeeb Alajmei,* Murtada Saleh Aljawad, Lei Wang, and Ashtiwi Bahri



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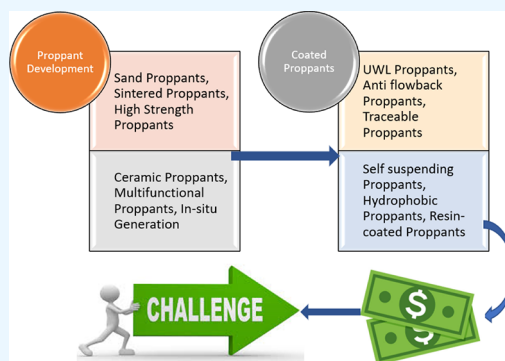
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ABSTRACT: The article provides a comprehensive overview of the selection of proppants in hydraulic fracturing for unconventional reservoirs. Proppants are essential for maintaining the conductivity of hydraulic fractures in well production. The industry has developed various types of proppants, including silica, ceramic, and advanced ultralightweight proppants. The paper covers the fundamentals of proppants, their types, compositions, geometries, and novel technologies for downhole pumping and placement of proppants, as well as in situ generation of proppants. Proppants are critical to improving hydrocarbon recovery as they keep the fractures open, which increases the overall hydrocarbon recovery. The selection of proppants must be tailored to the geological conditions of the reservoirs, and their performance is evaluated based on compatibility with the reservoir and rheological properties. Proppants must withstand closure stresses and diagenesis to ensure long-term fracture conductivity. Regarding proppant size, larger sizes maximize initial production, and smaller sizes allow for a slower long-term decline. Proppant crushing is a significant concern as it affects fracture conductivity. Factors influencing proppant crushing include proppant diagenesis, which refers to the chemical and physical changes proppants undergo in the reservoir. The development of various proppants, including sand, ceramic, resin-coated, curable resin-coated, lightweight, sintered, high-strength, and ultralightweight proppants, each with its advantages and limitations, is also discussed. Case studies from the Bakken and Marcellus Shale Formation demonstrate the impact of proppant selection on well production. Then, the economic optimization of proppant selection, considering factors like payout, internal rate of return, and net present value, is emphasized. The review also covers advancements in proppant technologies, such as multifunctional proppants, traceable proppants, and coated proppants. The potential of in situ proppant generation and the use of ultralightweight proppants are also discussed. The paper concludes with insights into the challenges and considerations for selecting proppants in unconventional reservoirs, stressing the importance of economic optimization and compatibility with fracturing fluids.



1. INTRODUCTION

Developing deeper and tighter conventional and unconventional hydrocarbon resources helps to meet the growing demand for gas and oil. By increasing the contact between the reservoir and the wellbore, hydraulic fracturing is used to achieve economic production rates in such tight formations. All applications involving hydraulic fracturing require two key components. The first is the solid particles needed to keep the fractures open after fracturing and to fill the resulting cracks. The second component is an engineered fluid system that is used to move these particles deep into the created cracks. Proppant is the term for the round, solid particles that keep the crack open and conductive.

Proppants are essential for the hydraulic fracturing process, which improves the extraction of gas and oil from underground reservoirs. Proppants are mainly used to maintain the open fractures after the pumping stops and the hydraulic fracturing fluid has been leaked into the formation. This increases the overall production rate as the hydrocarbons can flow freely

from the reservoir into the wellbore. Proppants are necessary to maintain the permeability of the fractures, which has a direct impact on the effectiveness of hydrocarbon production.¹

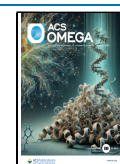
Proppants maintain the fractures open, allowing gas and oil to flow to the well. This might greatly improve the reservoir recovery, particularly for unconventional resources like shale gas and tight oil.² Ceramic, resin-coated sand, or sand are examples of proppants whose size and type have an impact on the design and optimization of the fracturing procedure. Because proppants have different strengths and conductivities, they must be customized to the specific geologic conditions of

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the reservoir.³ An essential method for improving the recovery of hydrocarbons from unconventional sources like shale is hydraulic fracturing. In the end, the well's productivity is determined by how effectively the fracturing process goes, which is heavily impacted by the fluid and proppant selection. Based on their overall performance in hydraulic fracturing, their compatibility with the reservoir and their rheological properties, the different types of fluids and proppants are evaluated.⁴

Proppants must withstand considerable closing stresses throughout the life of the well and be protected from crushing or deformation. The long-term conductivity of fractures is ensured by high-quality proppants that support continuous hydrocarbon production. Proppants are expensive when it comes to hydraulic fracturing, but when used properly, they can increase the longevity and efficiency of hydrocarbon production, which can lead to higher economic returns.⁵

This paper provides an in-depth analysis of the many proppant materials and functions that have been developed and used in the oil and gas industry for hydraulic fracturing. The operating window for each of these materials depends on factors such as specific gravity,⁶ diagenesis resistance,⁷ closure stresses⁸ and cost.⁹ To the best of the authors' knowledge, no recent publication has been published that compiles the experience and developments in the proppants field. The purpose of this study is to present an overview of the current proppant technologies, including the basic and complex forms, as well as the developments in proppant technology occurring recently for unconventional reservoirs.

2. PROPPANTS FUNDAMENTALS

While larger proppants maximize the initial production rate, smaller proppants allow for a slower long-term decline in production rate. Production is maximized by combining proppants of various sizes. It is always preferable to inject the smallest proppant first when using multiple proppant sizes. The ideal fluid and proppant combination for low proppant concentration lies in the region between small proppants in low-viscosity fluids and larger proppants in high-viscosity fluids.⁴

2.1. Size of Proppants. The proppant's size range is crucial for treating hydraulic fractures. Typically, proppant diameters range from 8 to 140 mesh (105 mm to 2.38 mm). The number of holes per linear inch of screen is known as the mesh size. The proppant is frequently referred to as just the sieve cut when discussing its size. The dimensions commonly used are presented in Table 1. The larger particle sizes are usually associated with increased fracture conductivity. To maximize the near wellbore conductivity, the typical fracture treatment will begin with a smaller particle size proppant and be tailored with a larger particle size proppant.¹⁰

Table 1. Proppant Dimensions, Adapted with Permission from Liang et al., 2016^{a10}

Mesh Size	Proppant Size
16/30	595 mm by 1190 mm
20/40	420 mm by 821 mm
30/50	297 mm by 595 mm
40/70	210 mm by 420 mm
70/140	105 mm by 210 mm

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A brief review of the various proppant kinds and amounts utilized in stimulation designs in the Bakken shale play was provided by Hu et al.¹¹ in 2011. Based on 270-day production data, the production rates of 72 wells in four separate fields were evaluated in four case studies that constituted the results. The same operator, similar fracture dates, and wells from the same field were used to ensure a fair comparison of the various proppant kinds and limit unnecessary impacts. Table 2 summarizes the production statistics from the wells. It was determined that greater output and estimated ultimate recovery (EUR) were obtained by utilizing a mixture of high percentages and large amounts of ceramic proppant.

2.2. Proppant Transport. To transport proppant effectively in the wellbore and into the fractures that are formed, proppant suspension in the fracturing fluid is crucial. According to the conventional opinion, which continues to rule the oilfield sector, fluid viscosity is the most crucial factor in the design of hydraulic fracturing fluids.

It has been discovered that fluid elasticity is one of the crucial factors influencing proppant suspension in hydraulic fracturing design.^{12–14} This perspective has led to the development of viscoelastic surfactant (VES) fluids.^{15,16} In 2004, a novel slurry viscometer^{17–19} was created that can measure the fluid's proppant transport properties and incorporate proppants. The proppant transport mechanism in slickwater fracturing in shale reservoirs is distinct. The low concentration of polymers in slickwater (up to 2 gpt) means that it lacks the high viscosity and elasticity needed to maintain the proppant in suspension. In this instance, proppant settles more quickly in static conditions, and proppant bank movement may be the primary driver of proppant transport.

In slickwater, three proppant transport processes have been suggested.^{20,21} Very little or no proppant is moved at very low velocities. Proppant grains roll or slide across the surface of the settled proppant bank at a faster speed (reputation creep). Proppant grains return to the flow stream after bouncing off the surface at even higher velocities in a process called saltation. According to Dufek and Bergantz,²² saltation is contingent upon the coefficient of restitution, which is the ratio of the object's exit velocity following a collision to its entry velocity. Deeper inside the crack will be reached by proppants that have a lower friction coefficient and a higher coefficient of restitution than other proppants. A crucial component of hydraulic fracturing's process for establishing and preserving fractures in subterranean rocks is proppant transport. The fracturing fluid pushes proppants—such as sand or ceramic beads—into the fractures to keep them open so that hydrocarbons can be extracted. Principles of fluid dynamics, in particular Stokes' law, which explains the motion of small spherical particles in a fluid, can be used to understand the mechanism of proppant transport.

2.3. Proppant Crushing. The crushing of the injected proppant can occur at multiple locations during a hydraulic fracturing process.²³ Proppants may chip and crack while being transported from the manufacturing site to the fracturing site, where they will be used in their final form. Most important is the kind that happens after the proppant is moved into the hydraulic crack that has been formed and is subjected to closure force from the layers of the overburden formation. Formation closure is the main cause of proppant crushing, especially in cases when the proppant is not evenly distributed. A crucial component of hydraulic fracturing is the effect of proppant crushing on fracture conductivity, which has a direct

Table 2. A Case Study on the Well Production on Bakken Shale Play with Different Types of Proppant Selection, Adapted with Permission from Liang et al., 2016^{a10}

Case Study	Group	Proppant Weight per Well (MMlb)	Type of Proppant	Mesh Size	Average Cumulative Production (BOE)		
					90 days	180 days	270 days
1	A	3.3	29% resin coated sand + 71% silica sand	(20/40 and 40/70) (20/40 and 40/70)	26,044	44,261	57,498
	B	3.16	28% ceramic + 72% silica sand	(20/40) (20/40 and 40/70)	29,722	50,790	63,732
2	A	2.7	30% lightweight ceramic + 70% silica sand	(20/40) (20/40 and 40/70)	36,538	68,570	92,764
	B	2.5	100% silica sand	(20/40 and 40/70)	19,892	33,712	45,954
3	A	3.9	100% ceramic proppant	(20/40) or 30/50 and 40/70)	61,351	104,170	137,117
	B	3.85	62% ceramic + 38% silica sand	(20/40) (40/70)	54,757	82,546	107,931
	C	2.9	35% ceramic + 65% silica sand	(20/40) (20/40 and 40/70)	39,226	63,676	81,964
4	A	2.6	32% ceramic + 68% silica sand	(20/40) (20/40 and 40/70)	56,251	86,127	109,627
	B	2.45	100% silica sand	No mesh information	23,134	40,244	54,362

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bearing on the productivity and efficiency of oil and gas extraction. When applied forces within fractures overcome the proppant material's strength, proppant crushing takes place. The proppant particles may shatter or crush as a result, resulting in several problems. To avoid proppant crushing, meticulous analysis of the regional horizontal stressed should be performed to accurately select the best proppant type for the stimulation treatment.

2.3.1. Impact on Fracture Conductivity. Smaller particles are produced when proppant particles crush might fill the pore spaces between bigger proppant grains. As a result, the proppant pack's permeability is decreased, which hinders the movement of hydrocarbons via the fractures. The fracture width can be decreased by using crushed proppants since they can compact more closely. Because of its narrower width, the fracture conductivity becomes lower overall. The fines produced by crushed proppants have the potential to move inside the crack and further clog the flow pathways, which will significantly reduce conductivity. The proppant may embed into the softer rock matrix as a result of the stress acting on it. This lowers the permeability of the proppant pack as well as the effective fracture width.

2.4. Proppant Diagenesis. Following the fracture of the reservoir rock and the transportation of proppants within it, the high pressure and temperature within the reservoir create an ideal environment for geochemical processes that initiate the diagenetic reaction, which fills the porosity of the proppant pack. As per the findings of,²⁴ proppant inserted into hydraulic fractures experiences variations in the chemical composition of the fluids present in the pore spaces as well as a developing stress field. The process by which proppant materials change chemically and physically after being injected into a hydraulic fracture in reservoir rock is known as proppant diagenesis. In oil and gas extraction operations, this procedure is essential for preserving the permeability and conductivity of fractures.

Except surface weathering, diagenesis refers to all chemical, physical, and biological alterations that occur in sediments following their original deposition as well as during and following lithification. To reduce the effect of diagenesis on fracture conductivity, additives such as biocides and scale inhibitors should be added to the fracturing fluid.

2.4.1. Chemical Reactions. Proppants can dissolve, precipitate or undergo other chemical changes as a result of chemical reactions with the fluids in the deposit. The

composition and structure of proppants can change if they come into contact with acidic or alkaline liquids, for example.

2.4.2. Physical Changes. Due to the stress and loading conditions in the fractures, mechanical degradation of the proppants can occur. The permeability of the supported crack can be impaired by this degradation, which can also lead to changes in the size and shape of the proppant grains.

2.4.3. Biological Effects. Proppants can be affected by biological activity in the subsurface, although less frequently. The integrity of the proppant can be altered by microbial activity that changes the chemical environment.

2.4.4. Hydraulic Fracturing Efficacy May Be Significantly Impacted by Proppant Diagenesis. Diagenetic processes could affect the proppant conductivity in several ways. First, it may cause a complete conductivity reduction of the fracture. The extraction efficiency of hydrocarbons may be affected if proppants disintegrate or dissolve, causing a decrease in the fracture's conductivity. In addition, proppant diagenesis could cause an unintended Formation Damage. New minerals may precipitate as a result of chemical interactions between proppants and formation fluids, which may close pores and decrease permeability. Finally, proppant pack longevity would be affected by proppant diagenesis. Diagenetic changes over time may cause compromises to the performance and durability of proppant packs.

3. RESULTS AND DISCUSSIONS

To optimize the hydraulic fracturing in unconventional wells, various types of proppants are used. Unconventional wells, for example, shale formations, have specific characteristics that influence the choice of proppants. Proppants come in a wide range of sizes and forms and have been developed with a substantial amount of material. Since covering all of these variations in this research would be extremely challenging, the primary focus will be on one of the most popular and fundamental types of proppants developed in the oil and gas sector.

3.1. Sand Proppants. Among the most often utilized proppants in hydraulic fracturing procedures involving unconventional shale formations. Because of their round grains and resistance to high temperatures and pressures, they are made entirely of silica sand. Although sand proppants are frequently utilized in hydraulic fracturing procedures, particularly in shale formations, there are several drawbacks to their

application. In comparison to other proppant kinds, such as ceramics, the conductivity of sand proppants could be lower.²⁵ Lower oil or gas flow rates from the formation to the wellbore may result from their low conductivity. High strains can cause sand particles to crush, particularly in deep wells with high overburden pressure. This may lead to a reduction in the fracture conductivity, which in turn may affect the performance of the well. There is a good probability that during production, produced fluids will return sand proppants to the wellbore. In the end, this may result in increased operating expenses, decreased well production, and formation damage. Sand proppants might not be appropriate in situations with strong chemicals or elevated temperatures. In these conditions, degradation of the sand grains may occur which reduces their effectiveness in propping open fractures and maintaining long-term conductivity. Hydraulic fracturing operations using sand proppants can have significant environmental impacts, including habitat destruction, air and water pollution, and disruption of ecosystems.²⁵ The average density of sand proppants is 2650 kg/m³, and they can withstand pressures of less than 6000 psi. They fall under the category of low strength, and low conductivity proppants that exist naturally. Even after sorting and sifting, they still retain a high degree of roughness and uneven size and shape. Long-term carbon dioxide exposure can affect them, particularly in harsh environments.²⁶

3.2. Ceramic Proppants. They are engineered particles made from materials like sintered bauxite, alumina, or other ceramics. Ceramic proppants offer several advantages over sand proppants, for example, higher resistance to crush and conductivity. However, they also have some limitations, when used in hydraulic fracturing in shale formations. Ceramic proppants are produced through high-temperature sintering or fusion of raw materials, which can be energy-intensive and necessitate the use of specialized manufacturing equipment. This intricacy might cause supply chain issues and consequent manufacturing delays. Ceramic proppants are heavier and denser than sand proppants, which can result in higher transportation costs. Handling and transporting ceramic proppants may require specialized equipment and infrastructure, adding to operational expenses. Some types of ceramic proppants may have limited availability or quality is variable, leading to uncertainty in their performance and reliability. Ensuring a consistent supply of high-quality ceramic proppants may pose challenges for operators, particularly in remote or emerging shale plays. While ceramic proppants have excellent crush resistance, the problem of flowback can still happen.²⁷ One of the proppants with the highest conductivity and strength is ceramic. Because of its production process, it has a regular size and shape as opposed to naturally occurring sand proppant. It typically produces a high permeability and porosity of fractures. It also shows extremely little deterioration and excessive heat resistance. The average density of ceramics varies from 2700 to 3400 kg/m³, depending on the kind. It can sustain pressures greater than 5000 psi, and in some situations, some varieties can endure pressures greater than 10,000 psi. Its remarkable endurance is a result of its extremely low carbon dioxide reactivity.²⁶

3.3. Coated Proppants. These proppants, typically made of sand, ceramic, or resin-coated materials, are injected into the fractures created during the fracking process to keep them open, thus facilitating the flow of hydrocarbons. When proppants come into contact with water, a substance coating them expands or reacts, encircling each particle in a suspending

liquid. Also, the soluble polymer that encapsulates them releases a suspending agent known as Encapsulated Proppants.²⁸

Proppants that have been coated come in two varieties at the moment, which are precured and curable. Six Precured coated proppants are made of glass spheres, quartz sand, or ceramic substrates that have had one or more polymer layers applied to them and then cured to create a three-dimensional network structure. The benefits of precured coated proppant are low density, smooth surface, good sphericity, and high compressive strength. Polyurethane, furan, epoxy, and phenolic resins are examples of common resin types.²⁹

The term "curable coated proppant" describes a layer of solid thermosetting resin that is applied on the proppant substrate, which can be glass spheres, quartz sand, or ceramic; the proppant that is injected into formation fractures. In the presence of an activator, in situ stress, and formation temperature, the resins soften, bond, and solidify to form a network structure. Curable proppants, such as epoxy and phenolic resins, are often used to effectively limit the flowback of tiny particles and prevent proppant flowback.³⁰ In Brazil, using low-density proppant can lower fluid leakage and the pumping speed of the fracturing fluid. In an oilfield offshore Brazil, 50 oil wells were completed using coated walnut shell proppant and coated porous ceramic proppant (Figure 1). The



Figure 1. Coated walnut shell proppant (a) and coated porous ceramic proppant (b), adapted with permission from Liu et al., 2023.²⁹ Copyright (2023, Energy & Fuels).

findings indicate that the settling rate of the low-density proppant is 75% slower than that of the traditional ceramic proppant. The least expensive and most successful completions are those that use low-density proppants.

The well's unique parameters, including pressure, temperature, and chemical content of the fracturing fluid and reservoir, can affect the effectiveness of the coating. Chemicals employed in the coating process have the potential to leak into the environment, endangering soil and groundwater. Proppants' ability to preserve fracture conductivity may be compromised over time by coating degradation, particularly in severe downhole conditions. Even with their unique design, coated proppants can still have flowback problems, in which the produced fluids carry the proppants back to the surface, resulting in inefficient operations and extra expenses for recycling and cleanup. A brief comparison between different proppants has been shown in Table 3.

3.3.1. Ultralightweight Proppant. Various sands, ceramics, and sintered bauxite are the most commonly used proppants because they are reasonably priced and are strong enough to withstand a wide variety of temperatures and stresses related to reservoir closure. Ultralightweight proppants (ULWP) have been suggested as a replacement for sand in several studies.^{31–34} The effectiveness of three ULWPs using slick-water fracturing fluid in Marcellus shale are assessed in this

Table 3. Comparison between Different Types of Proppants

Parameter	Sand (Uncoated)	Resin-Coated Sand	Ceramic Proppants	Resin-Coated Ceramic Proppants
Strength	Low	Medium	High	Very high
Cost	Low	Medium	High	Very high
Crush Resistance	Low	Moderate	High	Very high
Temperature Stability	Low (up to 150 °F/65 °C)	Moderate (up to 250 °F/121 °C)	High (up to 450 °F/232 °C)	Very high (up to 500 °F/260 °C)
Best Application	Shallow wells	Medium-depth wells	Deep, high-pressure wells	High-temperature, high-pressure wells
Flowback Control	Poor	Good (due to resin bonding)	Moderate	Excellent (combines ceramic strength and resin bonding)
Fines Migration	High	Low (resin helps reduce fines)	Low	Very low (due to both resin and ceramic properties)
Conductivity	Moderate	High	High	Very high
Environmental Impact	Low	Moderate (due to resin chemicals)	Moderate	High (higher energy production and resin chemicals)
Handling and Transport	Easy	Moderate (requires careful handling)	Difficult (due to weight)	Difficult (due to weight and coating care)
Usage Efficiency	High in low-cost, shallow operations	High in intermediate conditions	Very high in extreme conditions	Best choice for extreme well conditions

paper. Compared to traditional proppants (specific gravity: 1–2), ultralightweight proppants (ULWPs) are lighter but still strong enough to withstand reservoir stresses.^{31,34–36}

Alhemdi and Gu³⁷ used three light proppants (ULWP1, ULWP2, and ULWP3). The first one, known as ULWP1, and has the greatest elasticity and the lowest density. The second one is known as ULWP2. The third ultralight proppant is called ULWP3. According to,^{34,35} it has the highest density. The properties of these lightweight proppants have been mentioned in Table 4. Because of its uneven shape, ULW2 has

Table 4. Properties of ULWP's, Adapted with Permission from Yong-Cun et al., 2021^{a38}

Type of Proppant	ULWP1	ULWP2	ULWP3
Material	Polymeric	Ground walnut hull coated in resin	Porous ceramic covered in resin
Specific gravity	1.08	1.25	1.75
Shape	Spherical	Angular	Middle sphere
Mesh size	14/40	14/30	20/25

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a larger sieve size distribution than ULWP1 and ULWP3. Tests on conductivity, mechanical characteristics, and proppant deformation were carried out for the chosen ultralightweight proppant.

Ultralightweight (ULW) proppants offer several advantages in hydraulic fracturing. These proppants have an apparent specific gravity of less than or equal to 1.25, making them lighter than traditional proppants. This characteristic reduces proppant settling and requires low-viscosity fluids for proppant delivery, which can lead to increased propped length and improved fracture conductivity. In addition, natural materials like fruit pits, nut shells, and seed shells as well as deformable resin systems like furan, furfuryl alcohol, phenolic resins, epoxy resins, and thermoset polymers can be used as ULW proppants. The mechanical characteristics of the formation rock determine which proppant is best. ULW proppants are very useful for hydraulic fracturing underground reservoirs, as those that are mostly made of shale, chalk, coal, dolomite, limestone, etc. These proppants can also withstand closure stress requirements and resist diagenesis under downhole conditions. Overall, the use of ULW proppants can lead to an

enhancement in well's productivity and cost-effectiveness in hydraulic fracturing operations.³²

One type of proppant used in hydraulic fracturing to enhance the extraction of oil and gas from underground reservoirs is ultralightweight proppants (ULWPs). Compared to conventional proppants such as sand or ceramics, ULWPs have a lower density. This property can be particularly useful in lower pressure formations as they can be carried further into the fracture network with lower fluid pressure. Some ULWPs may contain a composite of lightweight ceramics and resin. ULWPs offer excellent transport properties due to their low density, allowing them to be used in less viscous fracturing fluids and reducing the overall cost of pumping the fluid. As they are able to reduce the embedment of the proppant and maintain the integrity of the proppant packing under closure stress, they can provide better fracture conductivity in certain circumstances.³³

While ultralightweight proppants (ULWPs) offer several advantages in hydraulic fracturing, they also have certain limitations and challenges that need to be considered. In general, ULWPs are less fracture resistant than conventional ceramic proppants. They could fracture or deform under heavy closure loads, which could ultimately reduce the conductivity of the fractures. It can be problematic for ULWPs to hold under extreme stress conditions, especially in deep wells where the pressure is much higher. Certain fracturing fluids and certain ULWPs can interact with each other, potentially altering the rheological properties of the fluid and the efficiency of transporting proppants. To ensure optimal performance, it is necessary to evaluate their compatibility. Due to their lower strength, ULWPs can integrate more easily into the rock matrix in softer rock layers. This can result in lower conductivity and a smaller effective crack width.³⁴

3.3.2. Antiflowback Proppants. Hydraulic fracturing uses antiflowback proppants, sometimes referred to as antiflowback proppants or just antiflowback agents, which are specialty materials. These proppants are made to keep proppants from flowing backward into the wellbore, keeping the fractures propped open to allow hydrocarbons to flow through them. Proppants may flow back into the wellbore as a result of pressure fluctuations that occur during production. Flowback can harm equipment, limit output, and lessen the effectiveness of fractures. To improve their capacity to remain in place, these proppants are coated or treated with specific material. They are

Table 5. Difference between Antiflowback and Ultralightweight Proppant

Category	Antiflowback Proppants	Ultralightweight Proppants
Definition	Proppants designed to prevent flowback into the wellbore by using resin coatings or fiber enhancements.	Proppants that are much lighter than conventional proppants, often made from materials like thermoplastics or lightweight ceramics.
Primary Function	Prevents proppant movement or flowback into the wellbore, ensuring fractures remain open and stable.	Designed to enhance fracture conductivity by maintaining position in the fracture even under low-pressure conditions.
Material Composition	Typically resin-coated sand, ceramic, or proppants with embedded fibers.	Made from lightweight materials like polymers, thermoplastics, or advanced lightweight ceramics.
Density	Higher density compared to ultralightweight proppants due to resin coating.	Significantly lower density, allowing it to be transported more easily by lower-viscosity fluids.
Cost	Generally more expensive due to the coatings and processing involved.	Can be cost-effective depending on the material used, but often cheaper than ceramic-based proppants.
Strength	High mechanical strength due to resin coating, suitable for high-pressure wells.	Typically lower mechanical strength, making them less ideal for extremely high-stress conditions.
Flowback Control	Excellent at preventing proppant flowback, reducing equipment wear and well cleanup costs.	Limited flowback control compared to antiflowback proppants; may require additional measures to prevent proppant migration.
Compatibility	May react with formation fluids or chemicals in the fracturing fluid, causing potential issues.	Highly compatible with various fracturing fluids and formation types due to inert material composition.
Applications	Ideal for wells with high closure stress and for minimizing flowback in challenging formations.	Suitable for low-pressure wells, unconventional reservoirs, and shallow formations where weight is a limiting factor.
Environmental Impact	May involve chemicals that require special handling and disposal procedures.	Lower environmental impact due to inert and nontoxic materials used in some ultralightweight proppants.
Handling and Transportation	Requires careful handling due to resin coatings and sensitivity to moisture.	Easier to handle and transport due to its lightweight nature and durability.
Performance in High-Stress Wells	Performs well under high-pressure and high-temperature conditions.	May not be suitable for extreme conditions as it can crush or deform under high stress.
Resistance to Crushing	High resistance to crushing due to resin coatings, maintaining fracture conductivity.	Moderate resistance to crushing; performance depends on the specific material used in the proppant.

frequently coated with resin or combined with fibers that cling to one another to inhibit movement.

One type of antiflowback proppant is resin-coated proppant, in which the resin binds the proppants together, preventing backflow. Additionally, the resin enhances the strength and endurance of the proppant by distributing stress. Another type is Fiber Enhanced Proppants, Fibers are combined with these proppants to form a network inside the fractures. The interlocking fibers offer more mechanical stability. Other ceramic proppants are advanced ceramic proppants with advanced coatings or structural enhancements. These proppants offer high strength and resistance to flowback due to their properties.³⁹ Table 5 shows the difference between antiflowback and ultralightweight proppants.

3.3.3. Traceable Proppants. In hydraulic fracturing or fracking, special substances known as traceable proppants are used to improve process monitoring and optimization. The purpose of these proppants is to help operators monitor their distribution within the fractures formed in the underlying rock formations.

Traceable proppants are designed to be fitted with tracers or markers that can be identified by a variety of sensor systems. They are used to monitor the positioning of the proppants, the shape of the fractures and the overall efficiency of the fracturing process. Chemical, radioactive or fluorescent tracers are all possible. Depending on the desired sensitivity and detection method, each type offers unique applications and benefits. Detection methods for radioactive tracers include gamma ray spectroscopy, chemical analysis for chemical tracers, and ultraviolet light detection technique is used for fluorescent tracers.⁴⁰

The sensitivity and precision of detection methods have a major impact on the effectiveness of traceable supports. Using low resolution or inaccurate data can lead to inaccurate fracture geometry and proppant placement. Subsurface factors such as high pressures, temperatures and chemical interactions can affect how well the tracers buried in the proppants work

and how detectable they are. One may have concerns about the durability of the tracers. Long-term monitoring is difficult as tracers can deteriorate or become less noticeable over time.⁴¹ Comparison between different types of traceable proppants has been shown in Table 6. It is believed that the geographic distribution of proppant could not be accurately reflected by the chemical tracer approach. When the tracer is coated on the proppant's surface, it will fall off under specific circumstances but not during the proppant migration process. A polymer containing a rhodamine 6G tracer can be applied to the surface of the quartz sand proppant (Figure 2).

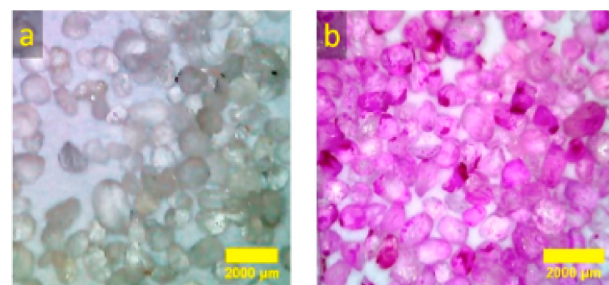
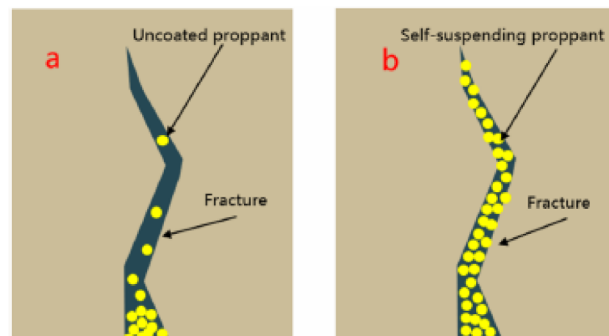
3.3.4. Self-suspending Proppants. Self-suspending proppant (SSP) is a type of proppant that can move independently into the fractures, eliminating the need for conventional gel-based carrier fluids. This technology makes hydraulic fracturing more efficient because it is simpler and uses less water and chemicals.⁴² Long-term suspension of self-suspended proppant in the fracturing fluid (Figure 3) guarantees the proppant's ability to travel widely throughout the crack.

Added viscosifiers or gelling agents are not necessary for SSPs to suspend in water or brine. The proppant particles are given certain coatings or treatments to give them this characteristic. SSP lessens the amount of water and chemicals needed for fracking by doing away with the requirement for gel-based fluids. This results in less of an impact on the environment and maybe less contamination of surface and groundwater. Because they can spread more evenly within the fractures, SSPs have the potential to improve fracture conductivity. This guarantees better total hydrocarbon extraction by effectively supporting the fissures.⁴³

3.3.5. Hydrophobic Proppants. An innovative method utilized in hydraulic fracturing to improve the efficacy and efficiency of oil and gas extraction is hydrophobic alteration of proppants. Proppants are solid substances that are introduced into the fracking fluid—typically sand or ceramic grains—to maintain the rock's fissures open after the high-pressure fluid is removed. Several advantages can be obtained by altering the

Table 6. Types of Traceable Proppants

Type of Traceable Proppant	Characteristics	Advantages	Limitations	Common Applications
Chemical Tracer Proppants	Embedded with chemicals that can be detected in fluid samples	- High sensitivity and precision- Nonradioactive, safer to handle	- Tracer signal can weaken over time- May be affected by chemical interactions in the subsurface	Production monitoring, water/gas breakthrough analysis
Radioactive Tracer Proppants	Embedded with low-level radioactive materials detectable by gamma-ray spectroscopy	- Nonradioactive, safer to handle - High detection sensitivity	- May be affected by chemical interactions in the subsurface - Strict regulatory controls	Fracture geometry mapping, proppant placement tracking
Fluorescent Tracer Proppants	Contains fluorescent materials that glow under UV light	- Can penetrate deep rock formations - Easy to detect using UV light- Cost-effective	- Environmental concerns - Limited detection range- Fluorescence can fade over time in harsh conditions - Fluorescence can fade over time in harsh conditions	Near-wellbore monitoring, short-term analysis
Magnetic Tracer Proppants	Contains magnetic particles that can be detected by magnetic sensors	- Effective in conductive environments - Noninvasive detection method	- Limited to specific geological conditions - High background noise can interfere	Geophysical surveys, fracture tracing in shallow zones

**Figure 2.** Conventional proppant (a) and tracer proppant (b), adapted with permission from Liu et al., 2023.²⁹ Copyright (2023, Energy & Fuels).**Figure 3.** Distribution of conventional proppants (a) and self-suspending proppants (b) in fractures, adapted with permission from Liu et al., 2023.²⁹ Copyright (2023, Energy & Fuels).

surface of these proppants to be hydrophobic, including decreased water retention, enhanced hydrocarbon flow, and less formation damage. Bestaoui-Spurr et al.⁴³ developed a neutral wet ceramic proppant to enhance reservoir fluid flow and clean up after fracturing using water-based fluids. The authors ensured that the proppant had surface wettability that was not affected by water or oil. That is, hydrophobic and oleophobic. To do this, a nanostructure was formed on proppant surfaces utilizing self-assembled monolayer (SAM) and wettability modification groups via spray covering.

To decrease water obstruction in the fractures, which could otherwise block the flow of hydrocarbons, hydrophobic proppants oppose water. Hydrophobic surfaces reduce the amount of water present, which improves the flow of gas and oil through the fissures. The dispersion and positioning of proppants inside the fracture network might be enhanced by hydrophobic alterations. The possibility of formation damage from water-sensitive clays and other minerals is decreased by hydrophobic proppants.⁴⁴ A hydrophobic substance can be applied to the proppant's surface to change its water-wet state into an oil-wet one, extending wells' water breakthrough times and boosting well productivity (Figure 4).

3.3.6. Resin-Coated Proppants. Resin-coated proppants consist of sand grains coated with a resin material. Resin-coated proppants offer advantages such as improved strength and reduced fine migration compared to conventional proppants. But, on the other hand, there are some disadvantages, particularly during the hydraulic fracturing of shale formations. Because of the additional cost of coating and the complexity of the manufacturing process, resin-coated proppants are generally more expensive than uncoated proppants. Resin coatings may degrade with time, especially in high-temperature or chemically aggressive environments

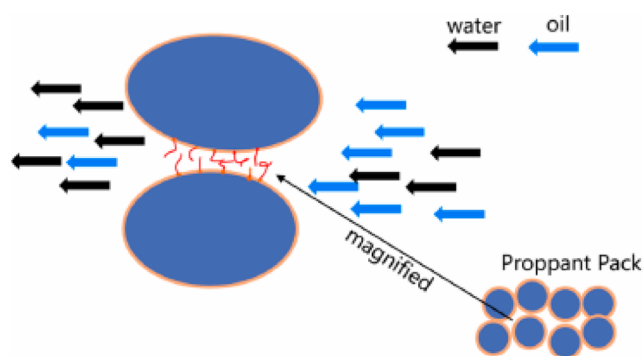


Figure 4. Oil and water pass through the hydrophobic proppant, adapted with permission from Liu et al., 2023.²⁹ Copyright (2023, Energy & Fuels).

which are common in shale formations. The degradation of resin may compromise the integrity of the proppant pack, leading to reduced well productivity and decreased fracture conductivity. Ensuring consistent quality and performance of resin-coated proppants can be challenging due to variations in resin coating thickness, adhesion, and curing properties. Quality control measures are essential to minimize variability and ensure optimal performance in hydraulic fracturing operations.⁴⁵ Resin coating the sand proppants can help provide some beneficial qualities. The average density of resin-coated sand proppants is 2550 kg/m³, which is somewhat lower than that of sand proppants. They are distinguished by their high angularity and irregular size, as well as by their pressure resistance of less than 8000 psi. Compared to sand proppants, they are less reactive to carbon dioxide, however, this depends on the kind of resin employed in the coating. They fall within the category of medium conductivity, and medium strength proppants.²⁶

3.3.7. Curable Resin-Coated Proppants. These proppants feature a resin coating that can be cured downhole using heat or other activation methods. Curable resin-coated proppants give few advantages over conventional resin-coated proppants like enhanced strength and conductivity, along with the ability to withstand high temperatures and harsh chemical environments. However, they also have some disadvantages, particularly in the context of hydraulic fracturing in shale formations. One of the challenging tasks is to achieve uniform and complete curing of resin-coated proppants in the downhole environment, especially in deep or high-temperature wells. Changes in the curing temperature, duration, and pressure can have an impact on the integrity and performance of the resin coating, which could result in inconsistent fracture conductivity and well productivity. Curable resin-coated proppants are made to survive extreme downhole conditions, such as high temperatures and chemical exposure, but resin degradation may still occur over time. The integrity of the proppant pack may be jeopardized by resin deterioration, which would result in decreased fracture conductivity and subpar well performance.⁴⁶

3.3.8. Nanocomposite Resin Coated Proppant. The type of proppant that is coated with a resin and cures under the heat and pressure of the reservoir, forming a consolidated packing that resists reflux. This type of proppant is called a curable resin-coated proppant. The type of proppant that contains a tough, fracture-resistant, thermoset resin coating that reduces reflux of the proppant without further curing in the wellbore is

called a precured resin-coated proppant. Ceramic-coated proppants are high-strength proppants that improve thermal stability and fracture resistance, making them ideal for high-temperature and high-pressure reservoirs.

The development of nanocomposite resin coated proppant, for use in hydraulic fracturing operations, has been explored by Haque et al.⁴⁷ The focus is on improving the strength and stability of the sand proppant with the use of the nanocomposite resin. This is a special type of coating that enhances the ability of the proppant to thermally and structurally withstand extreme conditions and makes it more resistant to invading fracturing fluids.

The authors explored the selection of the proppant used in hydraulic fracturing operations, revealing that sand was the preferred proppant in unconventional reservoirs in comparison to ceramics as it is cheaper and readily available. Nevertheless, the lower fracture toughness of sand proppant limits its usability in wells where closure stresses are higher. In order to avoid this, the authors have developed a nanocomposite resin coated sand proppant that improves the compressive strength, chemical resistance and long-term conductivity of the sand proppant.

Single-grain crushing test, optical particle size analysis, X-ray diffraction (XRD) to analyze the mineral content, and petrographic techniques to assess the microstructure were some of the methods they used to assess this proppant in depth. The southern white sand was shown to have a relatively more crushing strength owing to its monocrystalline structure than the brown sand from Texas, which is affected by some weak internal colored planes.⁴⁷ The proportions of this nanocomposite resin modifier assessed the proppant's performance in that API bicomp compressive strength sand increased by approximately 200%, however, compared to uncoated sand, long-term conductivity increased by 41%. Further addition of polymer coatings of such type containing nanomaterials would enhance conductivity by 100%. This section of the study deals with the experimental evaluation of the backing material in terms of sphericity and roundness, sieve analysis, API compression strength test, and under API long-term conductivity test. The authors also conducted the Loss on Ignition (LOI) tests that were used to assess the amount of resin that coated the sand substrate.

In conclusion, the authors stated that the development and testing of the nanocomposite resin coating technology have been achieved. It demonstrates enhanced performance of the proppant at elevated temperatures without reducing the exposure to fracturing fluid. This ensures that the coated sand can be used in the field in application under higher stress conditions. The nanocomposite resin coating appreciably enhances the performance of sand as a proppant in many applications.⁴⁸

Nanocomposite resin coating polymer has advancement over sand proppant in that it raises the mechanical strength, chemical and electrically conductive properties of the sand making it ideal proppant for hydraulic fracturing operations under harsh down hole conditions. Altering the surface saturation of resin-coated sand (RCS), in particular, has a considerable effect on its conductivity. Wettability characteristics change over time with surface penetration and since the proppant is in a fluid, a change in these characteristics can determine how well the proppant will bond to the fracturing fluid and formation thereby affecting the proppant's conductivity.

Altering the surface properties of RCS can enhance the fluidity of the proppant pack. This alteration can help to reduce the capability of the backing agent to retain liquid, thereby improving conductivity. That is to say, the modification in wettability could enhance the efficiency of the proppant in holding the fractures open by replacing some of the fluids present in the fracture, improving hydrocarbon outflow.

The authors refer to this observation by noting that the developers' art, specifically a modified surface treatment that has conductive implications which have been verified using an API long-term conductivity test. The test results indicated that the conductivity of resin-coated sand with hydrophobic properties altered (WA-RCS) was more than that of uncoated sand and standard RCS. Also, in the case of 40/70 mesh sand, water-wet sand was found to have more than 80% of the conductivity of raw sand, this was understood to be as a result of the change in water-wettability of the carrier surface. To conclude, decreasing baseline properties of surface wettability of resin-coated sand can be of great importance for improvement of proppant's performance in hydraulic fracturing processes.⁴⁹

3.4. Lightweight Proppants. To minimize proppant settling time and facilitate simpler placement in the crack, lightweight proppants are made to lower the density of the fracturing fluid. Certain materials are well suited for unconventional boreholes and can be used as lightweight proppants, such as hollow glass microspheres or ceramics. Lightweight proppants have some advantages, such as easier deployment and lower fracturing fluid density. However, they also have some disadvantages, especially when it comes to hydraulic fracturing in shale rock. Compared to heavy proppants such as sand or ceramic, the conductivity of light proppants can be lower. This can result in less oil or gas flowing from the formation into the wellbore, which in turn can lead to a lower production rate. Lightweight proppants tend to settle or segregate in the fracturing fluid, especially in vertical or deviated wells with long lateral sections. This can lead to an uneven distribution of proppants throughout the fracture network, which can cause problems with local conductivity. Certain lightweight proppants may be more likely to deform or fail under high loads because they have lower compressive strength than heavier proppants. Over time, this can lead to reduced fracture conductivity, embedment of the proppant and potential damage to the formation. Also, certain fracturing fluids or additives used in hydraulic fracturing may not mix well with light proppants.⁵⁰

3.5. Sintered Proppants. Strong, durable particles are produced by sintering or fusing raw materials at elevated temperatures to form sintered support materials. Their exceptional conductivity and compressive strength make them suitable for difficult reservoir conditions in unconventional wells. In addition, there may be certain restrictions on the use of sintered proppants in hydraulic fracturing in shale formations. The density of sintered proppants can vary depending on the manufacturing process and raw materials used. The fracture conductivity, settling behavior and movement of the proppant can be affected by variations in the density of the proppant. Because sintered proppants are denser and heavier than sand, handling, pumping, and transporting them during hydraulic fracturing operations can be more challenging. Moreover, certain fracturing fluids or additives used in hydraulic fracturing operations may not be compatible

with sintered proppants. As a result, it may result in inadequate fracture conductivity, decreased proppant transfer, and fluid loss, all of which lower well performance.⁵¹

3.6. High Strength Proppant. Costly, high-strength proppant (HSP) can withstand pressures of over 10,000 psi without experiencing any discernible crushing. The other popular types of propping material, such as natural sand or intermediate-strength proppant (ISP), are more economical, but they will crush if the proppant pack is subjected to a lot of stress during production or flowback.⁵² It can be applied in unconventional gas and oil areas, including tight gas, coalbed methane, and shale gas. Also, it could be suitable for harsh conditions where wells are subjected to high pressure and high temperature (HPHT). ISP keeps open cracks and permits more free movement of hydrocarbons, which improves fracking operations' productivity and efficiency. High-quality proppants are spherical and round, which helps them pack more efficiently and provides better permeability. It also provides resistance to formation and fracturing fluid chemical reactions, which aids in preserving the proppant's integrity and functionality over time. Low acid solubility is a common feature of well treatments to guarantee the proppant is chemically stable and does not dissolve in the presence of acidic fluids.

3.7. Multifunctional Proppants. Hydraulic fracturing technology has advanced significantly with the introduction of multifunctional proppants, which provide a range of other functions in addition to their conventional function of maintaining fissures open. These proppants are intended to enhance well performance, give more monitoring capabilities, and handle a number of issues related to oil and gas extraction. Multifunctional proppants are designed to increase fracture conductivity, which can improve hydrocarbon flow. Changes to the proppant's size, shape, and material composition are used to accomplish this. Certain multipurpose proppants contain compounds that release gradually over time. This feature reduces the need for frequent interventions by enabling continuous well treatment, such as minimizing scale buildup or mitigating paraffin deposition. Self-suspending proppants are the result of developments in nanocomposite coatings. By distributing proppants more evenly across the fracture network, these coatings enhance fracture support and placement. Smart microchip proppants are equipped with sensors that offer up-to-date information on fracture properties, including shape and position. Optimizing hydraulic fracturing operations and improving reservoir management methods need the use of this data. Traditional sand-based proppants can be replaced with more affordable and ecologically beneficial fly ash-based proppants, which are made from industrial by-products. These proppants have better mechanical qualities in addition to the benefit of waste reduction. It is possible to customize multifunctional proppants to enhance the multi-phase flow of reservoir fluids, such as water, gas, and oil. This improvement has the potential to greatly increase the overall well's efficiency and output rates.⁵³

3.8. In Situ Generation of Proppants. A relatively new technique in the realm of hydraulic fracturing for hydrocarbon extraction is the in situ production of proppants. By producing proppants inside the formation or close to the wellbore, this method eliminates the requirement to carry and inject conventional proppants from the surface, such as ceramic, sand, or materials coated in resin. Reducing logistical obstacles,

cutting expenses, and potentially raising the fracturing efficiency are the key benefits of this approach.

Several methods can be used to generate proppants like chemical reactions and thermal decomposition,⁵⁴ biological methods,⁵⁵ and nanotechnology.⁵⁶ Although in situ proppant generation offers many advantages, there are also significant disadvantages and difficulties to overcome. These limitations can impact the feasibility, effectiveness and overall success of using these techniques in hydraulic fracturing operations.

It can be a challenge to precisely control the chemical or biological processes used to produce supporting agents on site. Reaction rates and results can be affected by variations in reservoir conditions, including temperature, pressure, and chemical composition. It can be difficult to ensure uniform size and distribution of in situ produced proppants. Uneven fracture propagation and reduced fracturing efficiency can result from irregular proppant diameters. The performance and stability of the proppants produced can be affected by high temperatures and pressures in the reservoir. Under difficult conditions, some materials may deteriorate or lose their proppant qualities. The desired chemical reactions or micro-biological processes may be hindered by the presence of certain chemicals or minerals in the reservoir, which would reduce the efficiency of proppant formation.⁵⁷

In order for in situ proppants to withstand the abrasive conditions and forces into the fractures, they must be strong and durable. It can be difficult to ensure that the produced proppants meet these mechanical requirements. At high reservoir temperatures, proppants produced by sintering or thermal degradation must maintain their properties. It can be a challenge to ensure the thermal stability of these proppants. The introduction of microbes for the development of biological proppants may result in unintentional microbial growth or biofouling in the reservoir, which could affect overall production and the integrity of the reservoir.⁵⁸

4. CASE STUDIES

4.1. Marcellus Shale Formation Case Study. An important natural gas deposit is the Marcellus Shale formation, from which more gas can be extracted with the help of hydraulic fracturing. To facilitate the free flow of gas, proppants—usually sand or ceramic materials—are used to close the fractures created by hydraulic fracturing. To evaluate the effectiveness of lightweight and conventional proppants in terms of proppant transportation, settling rate, fracture conductivity and overall hydraulic fracturing efficiency, the researchers conducted laboratory tests and numerical simulations.³⁷

Transport Efficiency: Because light proppants are less dense than conventional proppants, the study indicated that they are more transportable within the fracturing fluid.

Settling Velocity: Light proppants showed slower velocities during the settling process, which may help minimize bridging and proppant settling during hydraulic fracturing operations.

Fracture Conductivity: By lowering proppant embedment and formation damage, light proppants may improve fracture conductivity and sustain long-term gas production rates, according to numerical models.

Economic Considerations: Using light proppants has potential cost savings due to decreased proppant requirements and increased well productivity. This is covered in the study along with other related economic consequences.

According to the study's findings, light proppants have potential as a workable substitute for traditional proppants in hydraulic fracturing procedures aimed at the Marcellus Shale deposit. They merit more research and field testing because of their enhanced transportability, slower settling velocities, and potential to increase fracture conductivity.

4.2. Proppants in Slickline Fluid. Using slickwater and relatively modest proppant (80/100 mesh, 40/70 mesh), early shale fracture techniques were successful in the Barnett play in producing financially sound wells.⁵⁷ However, for shale plays, other completion and treatment designs were needed; these designs frequently included larger proppants and more viscous fracturing fluids, such as cross-linked gel or linear gel.⁵⁸

In low permeability reservoirs, slickwater is one of the key components that makes horizontal wells with numerous hydraulic cracks successful. It aids in the formation of thin, long fissures. Furthermore, slickwater is inexpensive, readily available, and has minimal friction loss. Sand proppants, however, settle quickly and cannot fill the entire fracture length that has been generated. Consequently, only the area close to the wellbore will be supported.

In this instance, there is a noticeable distinction between the proppant and fracture lengths. In hydraulic fracture, the areal conductivity is determined by the proppant's distribution and transit. The productivity of the well would be adversely affected by small, propped sections. The gel can be added to water, among other methods, to enhance proppant transfer in hydraulic fractures.³⁷

4.3. Fracturing Case Study (China). Methods like microseismic monitoring and extensive hydraulic fracturing have been used with encouraging outcomes in China Unconventional Reservoirs. Pilot projects in the Ordos and Sichuan basins have demonstrated the effectiveness of certain techniques in boosting production, including as multistage fracturing in horizontal wells. Production rates could rise significantly as a result of advances in fracturing for complicated formations, like as Sichuan's Xujiahe Formation.^{59,60}

The Sulige gas field is one of the low-permeability and low-resistance reservoirs in the Ordos Basin where fracturing has increased single-well productivity. In the Xujiahe Formation, where customized fracturing methods addressed variable reservoir thickness, similar achievements have been documented. Following hydraulic fracturing, commercial gas flow has been shown in pilot projects in the Upper Yangtze region (such as the Weiyuan and Changning areas).⁶¹

In 2010, China used shale gas well fracturing for the first time. Instead of initially imitating the U.S. shale gas development model, China has created the technology and theory of fracture for midshallow shale gas during the past ten years, relying on the geochemical characteristics of Chinese shale gas reservoirs. In order to serve as a guide for future shale gas development in the nation,⁶² reviews the ten years of shale gas fracturing efforts in China, examines the evolution of fundamental theories, optimized design techniques, fluid systems, tools, and techniques, and summarizes the state and difficulties of shale gas fracturing in China.

In China, the shale gas fracturing fluid system is primarily water-based; it was initially imported (Schlumberger and BJ fluids, for example, were used in the fracturing of the first shale gas horizontal wells (201-H1 for CNPC and Jianye HF-1 for Sinopec) before the independently developed system became available. The fracturing fluid system changed from slickwater

to slick water gel (or linear gel) and viscosity-variable slick water. Between 2015 and 2017, the National Energy Administration (NEA) issued the Recommended Standards for Shale Gas Slick Water Fracturing Fluid,⁶³ formed a domestic slick water system for shale gas fracturing, and developed the first generation of water-soluble low-molecular polymer slick water fracturing fluid system and the second generation of reverse emulsion polymer slick water fracturing fluid system.

Additionally, Sinopec has created environmentally safe desorption slick water systems and acid slick water systems, both of which are crucial for fracturing shale with normal pressure and shale with a high carbonate content. The domestic slick water system was originally used by Sinopec and CNPC in 2012–2013 for the fracturing of Well Yuanye 1 and Well Wei 204, respectively. There are numerous difficulties facing the current fracturing fluid systems as a result of the extensive development of shale gas. In particular, the use of water-based fracturing fluids in shale gas resource areas needs to adhere to environmental protection and water resource supply regulations. Consequently, an effective working fluid for causing fractures and transporting sand with little or no water will become an inescapable choice. Techniques have evolved from conventional multistage fracturing to dense-cluster fracturing and temporary plugging fracturing.⁶⁴

5. COMPATIBILITY WITH FRACTURING FLUIDS

The fracturing fluid capacity to carry and move the proppant into the formation will depend on the proppant's characteristics. Fracturing Fluids have also been found to affect several proppants. To prevent issues, it is crucial to use a proppant whose qualities are compatible with the fluid.²⁶

5.1. Proppant Material. The fluid capacity to suspend and convey a particular concentration of the proppant will depend on the substance used to make it. For this reason, selecting the right proppant for the fracturing process is crucial. Conversely, if a weak proppant is selected in a high overburden pressure formation, it may fail, leading to fracture closure and, consequently, to the stop of production.

5.2. Proppant Shape. The proppant might have a spherical or cylindrical form. Each type's capacity to stay suspended in the fracturing fluid will be influenced by the proppant's roughness and angularity. The proppant's shape will affect its buoyancy in the fracturing fluid, which in turn will affect the upward force exerted on it.

5.3. Proppant Density. The forces exerted on the proppant to maintain its suspension in the fracture fluid will be affected by its density. There are two forces acting on the proppant particle, one pushing the proppant downward and other forces acting upward on it. Proppant settling may result from gravity's attempt to drag the proppant lower.⁶⁵ In contrast, buoyancy suspends the proppant in the fluid by working upward. Proppant characteristics such as material, density, and shape all affect the buoyancy force's capacity to defy gravity and sustain proppant suspension for safe hydraulic fracturing operations.

Increased polymer concentrations in fracturing fluids and the use of smaller-size proppants at low concentrations are necessary for a traditional fracturing treatment in such a highly stressed and difficult environment. Low fracture conductivity and a shorter effective fracture half-length are the consequences of this design. High polymer concentrations can also lead to additional damage to the proppant pack and are

difficult to clean up. These difficulties get worse in situations when the reservoir has limitations and is frequently unable to provide adequate energy for the fracturing fluids to be cleaned up.

Production is dependent on the almost infinite conductivity of the open channels rather than the proppant pack conductivity because the hydrocarbons move via the network of highly conductive open flow channels. Therefore, using the right engineering technique, it is possible to replace the HSP type of propping material with sand or ISP, which will save costs. Only near the end of the treatment, when the proppant is pumped conventionally at a particular concentration for a little amount of time to guarantee that dependable fracture conductivity in the crucial vicinity of the wellbore is established and maintained, will the ceramic proppant be required.⁶⁶

6. ECONOMIC ANALYSIS

Production will be higher from a longer, more conductive hydraulic fracture than from a shorter, less conductive fracture. Nonetheless, the design of fracture treatments involves balancing the economic advantages of increasing production with the higher costs associated with adding length and conductivity. Many methods for cost-benefit-based fracture design optimization alter variables like fluid and proppant quantities, types, concentrations, and flow rates. The pricing range for several proppant types is displayed in Table 7. A large

Table 7. Price of Different Types of Proppants, Adapted with Permission from Liang et al., 2016^{a10}

Proppant	Price, per lb.
Sand	0.019–0.058
RCS	0.195–0.245
Ceramics	0.27–0.90

^aCopyright (2015, Petroleum).

amount of the cost of treating a well is related to proppant cost. In small-scale sand proppant treatment designs, the proppant may make up 10–20% of the treatment's overall cost; however, in large-scale treatments utilizing synthetic-produced proppant, the proppant may cost more than 50% of the treatment's total cost. Similar reservoirs in the Wolf camp/Clearfork basin were examined by,^{67,68} who conducted a statistical analysis with an emphasis on proppant amount optimization, proppant type selection, and proppant mesh size. While the production of both cases is comparable, they discovered that natural sand proppant has the advantage of saving completion costs over ceramic proppant. The NPV in the ceramic proppant instance is dominated by the proppant cost and will drop as the amount of ceramic proppant increases.

Three common economic indicators that should be taken into consideration are payout, internal rate of return (IRR), and net present value (NPV).²⁰ The three indicators generally indicate identical capital allocation options in unconventional reservoirs since the first two years of unconventional well operation give between 30% and 40% of the expected recovery. For determining the well's NPV, IRR, and payout time, the authors created a simple economic model. Their approach is distinctive in that it uses an assumed declining curve in its NPV calculation to account for the revenue from oil and gas production. Economic optimization should ultimately guide the choice of proppant. Sand should never be preferred over

ceramic proppant unless there is a compelling economic argument.

7. CHALLENGES AND FUTURE PROSPECTS

In deep formations, proppants must be able to tolerate significant closing stresses. Under pressure, weak proppants may smash, reducing permeability and particles flowback. However, it is challenging to keep the cost and mechanical strength of proppants in balance. Inadequate flowback or placement during production can cause equipment damage and wellbore obstructions. Development of an economical means of stopping proppant movement is necessary in future. Proppants, particularly natural sand, have an adverse effect on the environment during mining and transportation, and incorrect treatment can contaminate nearby ecosystems. Proppant performance can be deteriorated by chemical reactions between proppants, fracturing fluids, and reservoir conditions (such as high salinity or temperature). Since high-performance proppants (such as ceramic or resin-coated) are costly, it is not recommended to be used in marginal wells. The creation of high-performing, reasonably priced substitutes should be investigated in the future to mitigate this issue.

Real-time information on temperature, pressure, and fracture geometry can be obtained from proppants that have sensors integrated into them. Nanotechnology may be also used in future applications to enhance communication and sensing capacities. Proppants that are renewable or biodegradable may reduce environmental impact. The advancement of coatings that enhance conductivity, withstand chemical deterioration, and stop particles migration should be considered. Resin coverings that cure themselves might be revolutionary. Also, employing sophisticated modeling and simulation tools to customize proppants to particular reservoir conditions is crucial before executing the fracturing job. Moreover, proppants with adjustable characteristics for various stress levels could be used for a wide range of formations. Another future prospect could be to focus on innovations in the extraction and processing of proppant raw materials to cut waste and reduce cost. Additionally, utilizing the concepts of the circular economy to recycle or repurpose proppants after their useful life.

In light of the growing volume of data, AI-driven analytics could be developed for improved fracture optimization and reservoir simulation. This could be done using predictive algorithms to determine which proppant types and amounts are best for a given formation. Finally, combining real-time monitoring systems with predictive performance data to enable adaptive decision-making.

8. CONCLUSIONS

This article provides a comprehensive overview of the selection of proppants for hydraulic fracturing operations in unconventional reservoirs. The main purpose of conventional proppants is to fulfill the requirements for closure stress and resistance to diagenesis under downhole conditions. The paper provides information on the wide range of proppants available, including silica, ceramics and technologically advanced options such as ultralightweight proppants. Overall, the paper provides valuable insight into the challenges and considerations associated with the selection of proppants for unconventional reservoirs, highlighting the importance of economic optimiza-

tion and compatibility with fracturing fluids in the decision-making process.

The choice of proppant for hydraulic fracturing has a significant impact on the productivity of the well and the conductivity of the fractures. Therefore, it is crucial to perform a comprehensive evaluation of the different types of proppants considering their performance in hydraulic fracturing operations, their compatibility with the reservoir properties and their rheological characteristics.

1. The density of the proppant plays a critical role in improving fracture conductivity. In the Marcellus Shale formation case study, research highlights the potential of using lightweight proppants as an alternative to conventional proppants in hydraulic fracturing treatments. Their properties, including improved transportability, lower settling velocity and potential to improve fracture conductivity, highlight their suitability for further investigation and field application.
2. Proppant particle size is among the most crucial properties for effective hydraulic fracture treatments. Typical fracture treatments begin with injecting smaller proppant particle size and gradually incorporating larger proppant sizes to optimize near the wellbore conductivity. In the Bakken shale play case study, it was suggested that utilizing a mixture of high percentages and large amounts of ceramic proppant leads to greater productivity and increased the estimated ultimate recovery.
3. Proppant crushing remains a significant concern during the hydraulic fracturing process, influenced by factors like transportation and formation closure stress. High-strength proppant emerges as the recommended choice due to its ability to withstand high pressures without crushing, distinguishing it from the other popular types such as sand and intermediate-strength proppant. However, sand should only be preferred over ceramic proppant with strong economic justifications.
4. The design of the hydraulic fracturing treatments needs a balance between maximizing economic benefits and managing the increased costs associated with enhancing fracture length and conductivity. Proppant selection should be guided by economic optimization, which includes analyzing factors such as payout, internal rate of return, and net present value, given that a significant portion of the well treatment cost is related to proppant.

AUTHOR INFORMATION

Corresponding Author

Shabeeb Alajmei – Department of Petroleum Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia; Center for Integrative Petroleum Research, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia; orcid.org/0000-0002-5816-4214; Email: alajmishn@kfupm.edu.sa

Authors

Mian Umer Shafiq – School of Mining and Geosciences, Nazarbayev University institution, Astana 010000, Kazakhstan

Murtada Saleh Aljawad – Department of Petroleum Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia; Center for Integrative Petroleum Research, King Fahd University of Petroleum &

Minerals, Dhahran 31261, Saudi Arabia; orcid.org/0000-0002-3540-6807

Lei Wang – State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, College of Energy, Chengdu University of Technology, Chengdu 610059, China; orcid.org/0000-0002-3090-1921

Ashtiw Bahri – Petroleum Engineering Department, Colorado School of Mines, Golden, Colorado 80401, United States

Complete contact information is available at:
<https://pubs.acs.org/10.1021/acsomega.4c09936>

Notes

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REFERENCES

- (1) Economides, M. J.; Nolte, K. G. *Reservoir Stimulation*; John Wiley & Sons, 2000.
- (2) Montgomery, C. T. Proppants and their role in hydraulic fracturing. In *Hydraulic Fracturing: Fundamentals and Advancements*, Gulf Professional Publishing, 2013.
- (3) King, G. E. Thirty years of gas shale fracturing: What have we learned?. In *SPE Annual Technical Conference and Exhibition*. SPE; 2010.
- (4) Cohen, C. E.; Abad, C.; Weng, X.; England, K.; Phatak, A.; Kresse, O.; Neuvonen, O.; Lafitte, V.; Abivin, P. Optimum Fluid and Proppant Selection for Hydraulic Fracturing in Shale Gas Reservoirs: a Parametric Study Based on Fracturing-to-Production Simulation. In *SPE Hydraulic Fracturing Technology Conference*; SPE, 2013.
- (5) Marongiu-Porcu, M.; Economides, M. J.; Holditch, S. A. Economic and Physical Optimization of Hydraulic Fracturing. *J. Nat. Gas Sci. Eng.* **2013**, *14*, 91–107.
- (6) Parker, M. A.; Ramurthy, K.; Sanchez, P. W. New Proppant for Hydraulic Fracturing Improves Well Performance and Decreases Environmental Impact of Hydraulic Fracturing Operations. In *SPE Eastern Regional Meeting*; SPE, 2012.
- (7) Weaver, J. D.; Parker, M.; Van Batenburg, D. W.; Nguyen, P. D. Sustaining Fracture Conductivity. In *SPE European Formation Damage Conference*; SPE, 2005.
- (8) Palisch, T.; Wilson, B.; Duenckel, B. New Technology Yields Ultra High strength Proppant. *SPE Prod. Oper.* **2014**, *30*, 76–81.
- (9) O'Driscoll, M. Proppant prospects for bauxite. In *Presented At 19th Bauxite & Alumina Conference*. 2013, 13–15.
- (10) Liang, F.; Sayed, M.; Al-Muntasheri, G. A.; Chang, F. F.; Li, L. A comprehensive review on proppant technologies. *Petroleum* **2016**, *2*, 26–39.
- (11) Hu, K.; Sun, J.; Wong, J.; Hall, B. E. Proppants Selection Based on Field Case Studies of Well Production Performance in the Bakken Shale Play. In *SPE Western North American and Rocky Mountain Joint Meeting*; SPE, 2014.
- (12) Bandara, K. M. A. S.; Ranjith, P. G.; Rathnaweera, T. D. Laboratory-scale study on proppant behavior in unconventional oil and gas reservoir formations. *J. Nat. Gas Sci. Eng.* **2020**, *78*, 103329.
- (13) Goel, N.; Shah, S. A Rheological Criterion for Fracturing Fluids to Transport Proppant during a Stimulation Treatment. In *SPE Annual Technical Conference and Exhibition*; SPE, 2001.
- (14) Hu, T. Y.; Chung, H.; Maxey, J. E. What is More, Important for Proppant Transport, Viscosity or Elasticity?. In *SPE Hydraulic Fracturing Technology Conference*; SPE, 2015.
- (15) Samuel, M.; Card, R. J.; Nelson, E. B.; Brown, J. E.; Vinod, P. S.; Temple, H. L.; Qu, Q.; Fu, D. K. Polymer-free fluid for fracturing applications. *SPE Drill. Completion* **1999**, *14* (4), 240–246.
- (16) Samuel, M.; Polson, D.; Kordziel, W.; Waite, T.; Waters, G.; Vinod, P. S.; Fu, D.; Downey, R. Viscoelastic Surfactant Fracturing Fluids: Application in Low Permeability Reservoir. In *SPE Rocky Mountain Regional/Low-Permeability Reservoirs Symposium and Exhibition*; SPE, 2000.
- (17) Waters, H. G.; Slabaugh, B.; Morgan, R. G.; Harris, P. C.; Health, S. J.; Powell, R. J.; Barrick, D. M.; Johnson, J. W. *Testing Device and Method for Viscosified Fluid Containing Particulate Material*, US 6,782,735 B2, 2004.
- (18) Harris, P. C.; Morgan, R. G.; Heath, S. J. Measurement of Proppant Transport of Frac Fluids. In *SPE Annual Technical Conference and Exhibition*; SPE, 2005.
- (19) Harris, P. C.; Walters, H. G.; Bryant, J. Prediction of proppant transport from rheological data. *SPE Prod. Oper.* **2009**, *24* (4), 550–555.
- (20) Mack, M. G.; Coker, C. E. Proppant Selection for Shale Reservoirs: Optimizing Conductivity, Proppant Transport and Cost. In *SPE Unconventional Resources Conference Canada*; SPE, 2013.
- (21) Mack, M.; Sun, J.; Khadilkar, C. Quantifying Proppant Transport in Thin Fluids e Theory and Experiments. In *SPE Hydraulic Fracturing Technology Conference*; SPE, 2014.
- (22) Dufek, J.; Bergantz, G. W. Suspended load and bed-load transport of particle-laden gravity currents: the role of particle-bed interaction. *Theor. Comput. Fluid Dyn.* **2007**, *21* ((*)), 119–145.
- (23) Weaver, J.; Parker, M.; Batenburg, D.; Nguyen, P. Fracture-Related Diagenesis May Impact Conductivity. *SPE J.* **2007**, *12* ((*)), 272–281.
- (24) Lee, D. S.; Elsworth, D.; Yasuhara, H.; Weaver, J.; Rickman, R. An Evaluation of the Effects of Fracture Diagenesis on Fracture Treatments: Modeled Response. In *The 43rd U.S. Rock Mechanics Symposium & 4th U.S. - Canada Rock Mechanics Symposium*; OnePetro, 2009.
- (25) Chen, M.; Zhang, S. Calculation method of proppant embedment depth in hydraulic fracturing. *Pet. Explor. Dev.* **2018**, *45* ((*)), 159–166.
- (26) Bremer, J. M.; Mibeck, B. A.; Huffman, B. W.; Gorecki, C. D.; Sorensen, J. A.; Schmidt, D. D.; Harju, J. A. Mechanical and Geochemical Assessment of Hydraulic Fracturing Proppants Exposed to Carbon Dioxide and Hydrogen Sulfide. In *The Canadian Unconventional Resources and International Petroleum Conference*; SPE, 2010.
- (27) Wang, Y.; Zhang, Y.; Deng, Q.; Yang, W.; Li, X.; Li, H. Mechanical Property and Damage Mechanism of Ceramics Proppants under Hydraulic Fracturing Conditions. *Energies* **2019**, *12*, 2355.
- (28) Wei, X.; Wang, Y.; Yang, T.; Song, Y. A Study on a New Type of High-Performance Resin-Coated Sand for Petroleum Fracturing Proppants. *Coatings* **2023**, *13*, 1841.
- (29) Liu, P.; Huang, Q.; Li, J.; Du, J.; Lu, X.; Liu, J.; Liu, C.; Lan, X. Review and Perspectives of Coated Proppant Technology. *Energy Fuels* **2023**, *37*, 3355–3370.
- (30) Barboza, B. R.; Chen, B.; Li, C. A review on proppant transport modeling. *J. Pet. Sci. Eng.* **2021**, *204*, 108753.
- (31) Brannon, H. D.; Starks, T. R. Maximizing Return-On-Fracturing-Investment By Using Ultra-Lightweight Proppants To Optimize Effective Fracture Area: can. Less Be More?. In *SPE Hydraulic Fracturing Technology Conference*; SPE, 2009.
- (32) Gu, M.; Mohanty, K. *Shale Fracturing Enhancement by Using Polymer-Free Foams and Ultra-Light Weight Proppants*, Doctoral dissertation; The University of Texas at Austin, 2013.
- (33) Gu, M.; Dao, E.; Mohanty, K. K. Investigation of Ultra-Lightweight Proppant Application in Shale Fracturing. *Fuel* **2015**, *150*, 191–201.
- (34) Gaurav, A.; Dao, E. K.; Mohanty, K. K. Ultra-lightweight Proppants for Shale Gas Fracturing. *J. Nat. Gas Sci. Eng.* **2021**, *85*, 103717.

- (35) Gaurav, A.; Gu, M.; Mohanty, K. K. Improvement of Fracturing for Gas Shales. *RPSEA Final Report* **2012**, 07122–38.
- (36) Mahoney, R. P.; Soane, D.; Kincaid, K. P.; Herring, M.; Snider, P. M. Self-suspending Proppant. In *SPE Hydraulic Fracturing Technology Conference*; SPE, 2013.
- (37) Alhemdi, A.; Gu, M. Application Investigation of Light Proppant in Hydraulic Fracturing of Marcellus Shale. In *SPE Eastern Regional Meeting*; SPE, 2021.
- (38) Yong-Cun, F.; Cheng-Yun, M.; Jin-Gen, D.; Xiao-Rong, L.; Ming-Ming, C.; Cheng, H.; Yu-Yang, L. A comprehensive review of ultralow-weight proppant technology. *Pet. Sci.* **2021**, *18*, 807–826.
- (39) Han, X.; Duenckel, R.; Smith, H. J.; Smith, H. D. An Environmentally Friendly Method to Evaluate Gravel and Frac Packed Intervals Using a New Nonradioactive Tracer Technology. In *the Offshore Technology Conference*; OTC, 2014.
- (40) Zhou, Y.; Liu, H.; Gao, J. J.; Fan, F.; Niu, Y. C.; Li, S. Z.; Mi, Y. Y.; Chen, S. Y.; Xu, Q. Coated proppants with self-suspension and tracer slow-release functions. *J. Pet. Sci. Eng.* **2022**, *208*, 109645.
- (41) Zhang, X.; Wang, Z.; Deng, J.; Zhao, H.; Zhuang, Y.; Zhang, Z.; Sun, X.; Lian, H.; Han, M.; Tian, Y. High-Temperature and Salt-Resistant Self-Suspending Proppant for Hydraulic Fracturing. *Energy Fuels* **2024**, *38* (1), 8620–8630.
- (42) Mahoney, R. P.; Soane, D. S.; Herring, M. K.; Kincaid, K. P.; Portilla, R. C.; Wuthridge, P.; *Self-Suspending Proppants for Hydraulic Fracturing* US 9,315,721 B2, 2014.
- (43) Bestaoui-Spurr, N.; Sun, S.; Williams, V.; Volk, A.; Nguyen, S. Using properties in nature to modify proppant surfaces and increase flow. In *SPE International Symposium On Oilfield Chemistry. Society Of Petroleum Engineers*; SPE, 2017.
- (44) Dahl, J.; Nguyen, P.; Dusterhoft, R.; Calvin, J.; Siddiqui, S. Application of microproppant to enhance well production in unconventional reservoirs: laboratory and field results. In *SPE Western Regional Meeting* 2015; SPE, 2015.
- (45) Azimian, A.; Salama, M. M. Quantitative Analysis of Proppant Flowback Using Frac Flowback Simulator, *Spe J.*, **2017**, *22*, 6.
- (46) Green, J.; Dewendt, A. W. First Proppant Designed to Decrease Water Production. In *SPE Annual Technical Conference and Exhibition*; SPE, 2018.
- (47) Haque, M. H.; Rajesh, K. S.; Mohammed, A. S. Nano-Composite Resin Coated Proppant for Hydraulic Fracturing. In *The Offshore Technology Conference*; OTC, 2019.
- (48) Alzanam, A. A. A.; Muhsan, A. S.; Abdulelah, H.; Mohamed, D.; Iglauer, S. Novel Nanocomposite Coated Proppants for Enhanced Scale Inhibition Lifetime in Tight Shale Formations. *Energy Fuels* **2022**, *36*, 14136–14147.
- (49) Velayati, M.; Sabouri, Z.; Masoudi, A.; Mostafapour, A.; Khatami, M.; Darroudi, M. Thermal Stability Investigation of Synthesized Epoxy-Polyurethane/Silica Nanocomposites. *Silicon* **2022**, *14*, 7541–7554.
- (50) Li, M.; He, F.; Li, Q.; Zhou, Y.; Li, S.; Chen, X. A New Lightweight Proppant and Its Application in Hydraulic Fracturing in Shale Gas Reservoirs. *Energy Fuels* **2020**, *34* ((7), 8), 664–8,675.
- (51) Krishnan, M. R.; Li, W.; Alharbi, B.; Alsharaeh, E. Recent developments on in-situ generated proppants for hydraulic fracturing operations: A critical review. *Geoenergy Sci. Eng.* **2024**, *242*, 213227.
- (52) Rahim, Z.; Al-Kanaan, A. A.; Kayumov, R.; Al-Jalal, Z. Effective Fracturing of High-Stress Reservoirs Using Nonstandard Proppant and Novel Technology. In *SPE Kuwait Oil & Gas Show and Conference*; SPE, 2017.
- (53) Al Aamri, G.; Christiawan, A.; Saldungaray, P.; Zaabi, A.; Al Hadhrami, I.; Ali, A.; Balushi, S.; Al Obeidany, R.; Yuyan, R. Multifunctional Proppants Enhance Well Economics and Minimize Intervention by Deploying Advanced Features During Fracturing Completion: Success Stories from Oman. In *SPE International Hydraulic Fracturing Technology Conference and Exhibition*; SPE, 2023.
- (54) Zhang, N.; Luo, Z.; Zhao, L.; Zhu, R.; Chen, W.; Liu, G.; Chen, X.; Xie, Y.; Cheng, L. Innovative Thermo-Responsive In-Situ Generated Proppant: Laboratory Tests and Field Application. *Energy Fuels* **2022**, *208*, 109514.
- (55) Fu, D.; Yu, Z.; Gao, K.; Duan, Z.; Wang, Z.; Guo, W.; Yang, P.; Zhang, J.; Yang, B.; Yang, F.; et al. Thermodynamic Analysis on In Situ Underground Pyrolysis of Tar-Rich Coal: Secondary Reactions. *ACS Omega* **2023**, *8*, 12805–12819.
- (56) Tabatabaei, M.; Taleghani, A. D.; Cai, Y.; Santos, L.; Alem, N. Using Nanoparticle Coating to Enhance Proppant Functions to Achieve Sustainable Production. In *SPE Annual Technical Conference and Exhibition*; SPE, 2019.
- (57) Baihly, J.; Altman, R.; Malpani, R.; Luo, F. Shale Gas Production Decline Trend Comparison Over Time and Basins. In *SPE/AAPG/SEG Unconventional Resources Technology Conference*; SPE, 2010.
- (58) Stegent, N. A.; Wagner, A. L.; Mullen, J.; Borstmayer Engineering a Successful Fracture-Stimulation Treatment in the Eagle ford Shale. In *Tight Gas Completions Conference*; SPE, 2010.
- (59) Xiaoqi, W.; Shipeng, H.; Fengrong, L. Carbon isotopic compositions of coal-derived gas in the Xujiahe Formation and Jurassic in the Sichuan Basin. *Pet. Explor. Dev.* **2011**, *38* (4), 418–427.
- (60) Qiulin, G.; Jianzhong, L.; Ningsheng, C. Modeling of the tight sandstone gas accumulation for the Xujiahe Formation, Hechuan-Tongnan Area, Sichuan Basin. *Pet. Explor. Dev.* **2011**, *38* (4), 409–417.
- (61) Qiulin, G.; Changqian, Z.; Ningsheng, C. *Evaluation methods for unconventional hydrocarbon resources*; Springer, 2011.
- (62) Zhao, J.; Ren, L.; Jiang, T.; Hu, D.; Wu, L.; Wu, J.; Yin, C.; Li, Y.; Hu, Y.; Lin, R.; et al. Ten years of gas shale fracturing in China: Review and prospect. *Nat. Gas Ind. B* **2022**, *9* (2), 158–175.
- (63) Hong, Y.; Honggang, C.; Fan, Y. Construction and prospect of China's shale gas technical standard system. *Nat. Gas Ind.* **2020**, *7* (4), 664–670.
- (64) Pengfei, C.; Chen, K. *An important step in the internationalization of China's shale gas technical standards*. Science Daily, 2021.
- (65) Yao, S.; Chang, C.; Hai, K.; Huang, H.; Li, H. A review of experimental studies on the proppant settling in hydraulic fractures. *J. Pet. Sci. Eng.* **2022**, *208*, 109211.
- (66) Barasia, A.; Pankaj, P. Tail-In Proppant and its Importance in Channel Fracturing Technique. *SPE Bergen One Day Seminar* SPE2014.
- (67) Yang, M.; Liu, X.; Jiao, D.; Economides, M. J. Hydraulic Fracture Design Flowse Proppant Selection. *SPE Western Regional & AAPG Pacific Section Meeting 2013 Joint Technical Conference* SPE2013.
- (68) Yang, M.; Economides, M. J.; Wei, C.; Gao, C. Hydraulic Fracture Design Flowse Proppant Selection. *SPE Western Regional & AAPG Pacific Section Meeting 2013 Joint Technical Conference* SPE2013.